

# Scientific Potential of Enhancing the Integral-Field Spectrometer SPIFFI with a Large Detector and High Spectral Resolution

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**Abstract.** SPIFFI is the near-infrared integral-field spectrometer for the VLT. Assisted by the SINFONI adaptive optics module, the instrument will be offered to the astronomical community in 2004. We outline the scientific rationale for infrared integral-field spectroscopy at the VLT, and specifically for the enhancement of SPIFFI with a larger detector and higher spectral resolution gratings. We give examples of a broad variety of astronomical research which will gain specifically from the high angular and spectral resolution provided by SPIFFI, including studies of high red-shift galaxies, merging galaxies, starburst galaxies, superstar clusters, galactic nuclei, extra-solar planets, and circum-stellar discs.

## 1 Introduction

Integral-field spectrometers record simultaneously the spectrum of every image point of a two-dimensional field of view. The result of an observation with an integral-field spectrometer is a three-dimensional data cube, with two spatial dimensions and one spectral dimension. In this respect data from integral-field spectrometers are similar to the results from observations with traditional imaging spectroscopy techniques like slit-scanning with long-slit spectrometers or a tunable Fabry-Perot-filter in an imaging camera. However, integral-field spectrometers have two significant advantages over these classical techniques. First, integral-field spectrometers are far more efficient in many applications. These are observations, in which astronomers are interested in the spectrum of a comparatively small number of spatial pixels of an extended object, but with large spectral coverage. In such observations long-slit spectra or Fabry-Perot images waste the majority of pixels on blank sky. Second, integral-field spectrometers are often easier to calibrate, specifically in the infrared. The spectra of every image point of the two-dimensional field of view are recorded simultaneously, and varying atmospheric transmission and absorption affect all spectra in the same way. The calibration of adaptive optics observations with classical spectrometers is even more difficult, because the point spread function can vary significantly from exposure to exposure.

Because of the obvious advantages of integral-field spectroscopy at infrared wavelengths, the Max-Planck-Institut für Extraterrestrische Physik (MPE) de-

veloped in the mid 1990's the worlds first cryogenic integral field spectrometer 3D (Weitzel et al. 1996). This instrument was successively upgraded to higher spectral resolution, and has been operated with fast tip-tilt compensation (Thatte et al. 1995), and high-order adaptive optics (Anders et al. 1998; Davies et al. 2000). The success of this instrument led to the development of the successor SPIFFI (Eisenhauer et al. 2000), foreseen for operation at the Very Large Telescope (VLT) of the European Southern Observatory (ESO). The following sections of this article introduce the instrument, outline the scientific drivers, specifically for an upgrade to higher spectral resolution and a larger detector, and sketch the realisation of this upgrade.

## 2 Near-Infrared Integral-Field Spectrometer SPIFFI

SPIFFI (SPectrometer for Infrared Faint Field Imaging) is a fully cryogenic integral-field spectrometer for the near-infrared wavelength range from 1.1 – 2.45  $\mu\text{m}$ . The spectrometer is part of the SINFONI (SINgle Faint Object Near Infrared Investigation) instrument for the VLT, which also includes a modified version of the adaptive optics MACAO (Donaldson et al. 2000). SINFONI is a joint project of MPE, responsible for the design and manufacturing of SPIFFI, and ESO, responsible for the design and manufacturing of the SINFONI AO (Adaptive Optics) Module, with a contribution by NOVA to the adaptive optics module. Here we give a brief summary of the main characteristics of SPIFFI. An extensive technical description can be found in Eisenhauer et al. (2000), Mengel et al. (2000), Tecza et al. (2000a) and references therein.

The heart of SPIFFI is an image slicer (Tecza et al. 2000), which splits the image into 32 small slitlets, and rearranges them into a 30 cm long pseudo slit. This pseudo long slit is then fed into an infrared spectrometer, which consists of a three-mirror collimator, a grating wheel with four different diffraction gratings, a lens camera, and a Rockwell HAWAII 1024<sup>2</sup> detector. The gratings are optimized for the three near-infrared J, H, and K atmospheric bands, and offer a spectral resolution ranging from approximately 2000–4000. With this resolution, SPIFFI allows effective avoidance of the atmospheric OH lines, which dominate the broad-band background at these wavelengths. Pre-optics provide three different image scales, ranging from 250 mas/pixel for seeing limited observations down to 25 mas/pixel for adaptive optics assisted observations at the diffraction limit of the telescope. A so-called sky-spider allows simultaneous observations of the sky background. All opto-mechanics are cooled with liquid nitrogen.

Table 1 summarizes the point-source sensitivity of SPIFFI (Mengel et al. 2000). The limiting magnitudes are calculated for a signal-to-noise ratio of five at the full spectral resolution of approximately 4000. For seeing-limited observations, we integrate over the seeing disc, assuming the median seeing of 0.69 arcsec on Paranal. The numbers for adaptive optics assisted observations are calculated for a Strehl ratio of 15% in J and H Band, and 25% in K-Band, and integrating over the diffraction-limited core. We assume a total integration time of 2 hours (12 exposures of 600s).

**Table 1.** Point source sensitivity of SPIFFI.

Wavelength Band	Pixel Scale	Limiting Magnitude	
		no OH Avoidance	with OH Avoidance
J	Seeing	19.9	20.4
	Adaptive optics	19.1	19.2
H	Seeing	18.9	20.1
	Adaptive optics	18.5	18.6
K	Seeing	17.9	18.0
	Adaptive optics	18.0	18.0

### 3 Scientific Potential of SPIFFI and Drivers for Higher Spectral Resolution

With the sensitivity of a fully cryogenic instrument, a spectral resolution of approximately 100 km/s, and the diffraction-limited angular resolution of an 8 m telescope, SPIFFI and SINFONI will push forward astronomical research in many areas. A major domain will certainly be the exploration of galaxy dynamics in the near and far universe. This is also the area which will gain significantly from a spectral resolution of approximately 10000, or equivalently 30 km/s. The following sections summarize the scientific potential of SPIFFI, with emphasis on the gains provided by higher spectral resolution.

#### 3.1 High Redshift Galaxies

For the time being, Lyman-break galaxies are the best studied tracers of the cosmic star-formation history (Steidel et al. 2001). However, even fundamental properties of these galaxies are still unknown: What is the spatial extent of the star-forming regions? Are these galaxies dominated by a rotationally supported disc, or by irregular motion? And what is the dynamical mass to light ratio of these objects? The reason for our ignorance is the lack of optical emission lines, which are shifted to the K-band at redshifts larger than three. Only the latest generation of near-infrared spectrometers at the VLT and Keck can measure the velocity dispersion and a hint of the rotation curve in a few of these galaxies (Pettini et al. 2001). However, these objects exhibit an irregular spatial structure, and single slit positions cannot provide the necessary two-dimensional information for accurate rotation curve or velocity dispersion measurements. Integral-field spectroscopy will overcome this restriction. In addition, these objects often have a size smaller than the slit width in seeing-limited spectroscopy, and fine pixel scales and higher spatial resolution as provided by SINFONI and SPIFFI will help in better understanding the nature of these objects. Since the masses of these young galaxies are modest, their velocity dispersions are only of order 50–100 km s<sup>−1</sup>, and SPIFFI observations of these objects will require a spectral resolution of approximately 10000.

### 3.2 Merging Galaxies

The evolution of galaxies is strongly affected by interactions with neighbouring systems. In particular, merging galaxies initiate dramatic processes, including triggering of starbursts, lighting up of galactic nuclei, and changes in Hubble-type. For such complex systems, imaging spectroscopy is crucial for understanding the dynamical structure. Because the appearance of merging galaxies is very much dominated by local dust absorption or star-formation, the observer may be biased in positioning the slit in traditional spectroscopy.

NGC 6240 is the local template for a pair of merging galaxies (Tecza et al. 2000, Van der Werf et al. 1993). With its total luminosity of  $6 \times 10^{11} L_{\odot}$ , this galaxy nearly fulfils the criteria for an ultra-luminous infrared galaxy. At a distance of only 97 Mpc, it is one of the few systems which allows detailed study of the underlying processes. With integral-field spectroscopy, the observer can directly derive radial velocity and velocity dispersion maps for the entire light distribution. In addition, the variety of spectral features in the K-band allows the separate investigation of gaseous (from the  $H_2$  emission lines) and stellar components (from the CO absorption bands) in a homogeneous way. The  $H_2$  emission lines have width of up to 550 km/s FWHM which must be the superposition of several narrower lines, as is also the case for the CO absorptions bands. With higher spectral resolution the individual components will be resolved.

### 3.3 Starburst Galaxies

Merging galaxies are extreme examples of how the interaction between two galaxies impacts their future evolution. But also non-destructive encounters can alter the appearance of a galaxy in significant ways. The prototypical starburst galaxy M82 provides an example, in which the encounter with its neighbor M81 has triggered extraordinarily strong circumnuclear star-formation. While the global properties of M82 are well-known from classical infrared and optical spectroscopy (Rieke et al. 1993), the detailed distribution and history of star-formation cannot be derived from modelling the global properties alone. Observation of the circum-nuclear starbursts with an integral-field spectrometer (Förster-Schreiber et al. 2001) reveals a complex spatial distribution of star-forming regions with different ages. This data allows modeling of the individual clusters, which removes many ambiguities from the global models. The multiplex advantages of integral-field spectrometers over classical techniques reduce the necessary observing time significantly for such regions, because typically a couple of star-forming regions are covered in a single exposure.

### 3.4 Super Star Clusters

The duration of starbursts is typically only a few million years, but the remnants of the so called super star clusters – the largest star-forming regions in starbursts – may evolve to globular clusters. A severe counter argument against this scenario, however, might be the frequency of stellar masses in starbursts and

globular clusters. Although no firm conclusion has been reached for starbursts (Eisenhauer 2001; Gilmore 2001), there is strong evidence that these regions form proportionally fewer low mass stars with masses around  $1 M_{\odot}$  than typically observed in our Galaxy. Globular clusters, however, are known to contain a large number of such low-mass stars. Measurement of the initial mass function in super-star clusters, or even the ratio of high and low mass stars, would thus give strong evidence in favour or against the hypothesis of the evolution of starburst super-star clusters into globular clusters. While the light traces the high mass stars in these young clusters, the frequency of low-mass stars can only be measured through the total mass of the cluster, so that dynamical mass determinations are required. However, there are only few super star cluster with dynamical mass measurements, for example in NGC 1569 and NGC 1705 (Ho & Filipenko 1996), or in the Antennae galaxy (Mengel et al. 2001). Because many of these clusters are highly obscured, near- infrared spectroscopy will significantly enlarge the sample. The typical velocity dispersion of these clusters is several 10 km/s, and they are marginally resolved in HST images. With a spectral resolution of approximately 10000, SPIFFI and SINFONI would be ideal for the observations of these clusters at adaptive optics pixel scales.

### 3.5 Supermassive black holes in Galactic Nuclei

Dynamical evidence for the presence of large dark mass concentrations in the nuclei of normal spiral galaxies has been mounting in recent years (e.g., Gebhardt et al. 2000; Ferrarese & Merritt 2000). In most cases, the central dark mass concentrations (presumed to be supermassive black holes) are inactive or dormant, and their presence can only be inferred from gas kinematic (e.g., Miyoshi et al. 1995; Marconi et al. 2001) or stellar dynamic (e.g., Kormendy et al. 1996; van der Marel et al. 1997) measurements. Gas kinematic measurements are often hard to interpret due to complex gas motions which can be perturbed by non-gravitational effects such as shocks, magnetic fields, inflows etc. An unambiguous Keplerian velocity profile of the gas at radii close to the black hole can only be observed in a few cases, such as the water maser line observations of NGC 4258 by Miyoshi et al. (1995). Stellar dynamics measurements are more robust, and have been carried out for a number of elliptical galaxies (e.g., Kormendy & Richstone 1995). However, this is difficult to do for spiral galaxies, due to the high dust extinction blocking direct view of the nucleus at visible wavelengths. The radius of influence of a black hole is small (de Zeeuw 2000), so high spatial resolution (or adaptive optics) is needed to see the increase in central velocity dispersion indicative of a central dark mass concentration. The obscuration in the nuclear regions of most spiral galaxies can prevent correct identification of the dynamical nucleus, which is often not the brightest visible (or near infrared) unresolved nuclear source, as demonstrated for M83 (Thatte, Tecza & Genzel 2000). In addition, the stellar orbits are often complex, and two-dimensional velocity dispersion and rotation maps are required to correctly account for anisotropy effects. SINFONI can overcome all these limitations and make a significant impact in establishing the demography of supermassive nuclear dark masses in nearby spiral galaxies.

### 3.6 Brown Dwarfs and Extrasolar Planets

In the next years, all major observatories will have high-order adaptive optics systems available at their large telescopes, and certainly many new brown dwarf and giant planet candidates will be identified in the proximity of nearby stars. The first example of such an object was the brown dwarf Gliese 229b (Nakajima et al. 1995; Geballe et al. 1996). But broad-band photometry alone will not allow the accurate determination of the spectral type of these objects. Reliable mass estimates require spectroscopic classification. However, long-slit spectroscopy of such objects, which are several magnitudes fainter than the primary components, and which lie in the remaining seeing halo of the partially-corrected adaptive optics images, will be difficult, because accurate deconvolution of the primary and secondary component requires the two-dimensional information of the underlying point spread function. Integral-field spectroscopy with SPIFFI and SINFONI will provide the spectra and the two-dimensional point spread function simultaneously, and will thus simplify significantly spectroscopy at or close to the diffraction limit of an 8 m telescope.

### 3.7 Circum-stellar Discs

Planets are supposed to form proto-planetary discs, many of which have been discovered with the Hubble Space Telescope (McCaughrean 1995). At the distance of the Orion nebula, the emission from the molecular hydrogen in such discs typically extends over about one arc-second. The K-band hydrogen emission lines could be the ideal tracer of the rotation of the disc, because at these wavelengths the SINFONI adaptive optics system provides the best correction of the atmospheric turbulence. However, the present spectral resolution of SPIFFI is too low for measuring the rotation of these discs. For a 5 solar mass star in Orion, the Keplerian velocity would be 4 km/s at a radial distance of 1 arc-second, and 15 km/s at a distance of 0.1 arc-seconds. These observations would benefit from spectral resolutions (in excess) of 10000.

## 4 Advantage of a Larger Detector

In its present configuration, SPIFFI incorporates a Rockwell HAWAII 1024<sup>2</sup> array. In order to make maximum use of the detector and have a thousand spatial elements, the spectra of SPIFFI are not Nyquist sampled, but the slit width corresponds to one detector pixel. In consequence, observations with SPIFFI at its highest spectral resolution require two exposures, in which the spectra are offset by half a pixel (Eisenhauer et al. 2000). This technique was applied successfully in the precursor instrument 3D, but requires good observing conditions and additional data processing. In addition, the image motion between the two exposures should not exceed a fraction of a pixel, which puts strong requirements on the tracking accuracy and mechanical stiffness of the system. An upgrade to the Rockwell HAWAII 2048<sup>2</sup> will overcome the problems with the

spectral dithering by providing Nyquist sampled spectra in a single exposure. The number of spatial elements will not be increased, so that two detector pixels cover one sky pixel.

An additional advantage of a larger detector is a less stringent requirement on the image quality of the spectrometer camera. Not only is the light for a spectral resolution element now spread over two pixels instead of one pixel, but also the f-number of the spectrometer camera is significantly increased from approximately 1.6 to 3.1. The upgrade to a larger detector would also open an opportunity for the implementation of an array manufactured using molecular beam epitaxy. These arrays are expected to have a negligible dark current (Kozlowski et al. 1998) well below the  $0.1 \text{ e}^-/\text{s}$  dark current of the present HAWAII 1024<sup>2</sup> arrays, which are grown in the traditional liquid phase epitaxy technique. This upgrade will thus significantly increase the sensitivity in adaptive optics assisted observations at the smallest pixel scale of 25 mas/pixel, in which the typical sky brightness in the H-band between the OH lines corresponds to  $0.0015 \text{ e}^-/\text{s}$ .

## 5 Upgrade Plan for SPIFFI

The present planning foresees a standalone guest-phase operation of SPIFFI without the AO module for 2002, and commissioning of the joint SPIFFI and SINFONI instrument in late 2003. Regular observations will start in 2004. Depending on progress of the instrument, we propose the upgrade of SPIFFI prior to the commissioning of the SINFONI facility instrument.

The enhancement of SPIFFI with a larger detector is independent of an upgrade to higher spectral resolution. A larger spectral resolution requires the exchange of one or several of the four gratings in SPIFFI. The design of SPIFFI accounts for this possibility by having a comparatively large diameter of the collimated beam of approximately 100 mm. In K-band, a spectral resolution of approximately 11000 can be achieved either with a grating with 100 grooves/mm, operated in fourth order, or a grating with 200 grooves/mm, operated in second order. Because of the small separation of adjacent grooves – twice the wavelength – in the latter case, polarization effects become dominant (Loewen et al. 1977) and need to be calculated before a decision on the grating design can be made. In both cases the larger anamorphic magnification of such a high resolution grating will restrict operation to pixel scales smaller than 200 mas, otherwise vignetting of the spectrometer camera would degrade the sensitivity of the instrument.

The upgrade to the Rockwell HAWAII 2048<sup>2</sup> detector implies exchange of the spectrometer camera and the detector readout board. Because the pixels of the larger detector have almost the same size ( $18 \mu\text{m}$  vs  $18.5 \mu\text{m}$  in the HAWAII 1024<sup>2</sup> detector), the focal length of the camera must be increased from approximately 180 mm to 350 mm. This simplifies the lens optics, but requires a fold mirror because of the tight design volume available in the SPIFFI cryostat. A preliminary five-lens design with spherical lenses made from Barium Fluoride and the Schott glass IRG2 was foreseen since the early design phase, so that the upgrade to a larger detector is straightforward.

## 6 Summary

The adaptive optics SINFONI and its integral-field spectrometer SPIFFI will provide unprecedented imaging spectroscopy at the diffraction limit of an 8 m telescope. The high sensitivity, the broad wavelength coverage, and several image scales optimize this instrument for the observation of a variety of objects from the early universe to nearby exo-planet candidates. However, many applications – specifically the observation of the dynamics in complex galaxy systems – will benefit strongly from an enhanced spectral resolution of about 10000. In addition, the upgrade to a larger detector with lower dark current will simplify observation and data-reduction, and increase the sensitivity of the instrument at adaptive optics pixel scales. This upgrade of SPIFFI is straightforward, and could be implemented in an early phase of the facility mode operation.

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